



# Measurement of prompt $\psi(2S)$ production cross sections in proton–lead and proton–proton collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration<sup>\*</sup>

CERN, Switzerland

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## ABSTRACT

Measurements of prompt  $\psi(2S)$  meson production cross sections in proton–lead (pPb) and proton–proton (pp) collisions at a nucleon–nucleon center-of-mass energy of  $\sqrt{s_{NN}} = 5.02$  TeV are reported. The results are based on pPb and pp data collected by the CMS experiment at the LHC, corresponding to integrated luminosities of  $34.6 \text{ nb}^{-1}$  and  $28.0 \text{ pb}^{-1}$ , respectively. The nuclear modification factor  $R_{pPb}$  is measured for prompt  $\psi(2S)$  in the transverse momentum range  $4 < p_T < 30 \text{ GeV}/c$  and the center-of-mass rapidity range  $-2.4 < y_{CM} < 1.93$ . The results on  $\psi(2S)$   $R_{pPb}$  are compared to the corresponding modification factor for prompt  $J/\psi$  mesons. The results point to different nuclear effects at play in the production of the excited charmonium state compared to the ground state, in the region of backward rapidity and for  $p_T < 10 \text{ GeV}/c$ .

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## 1. Introduction

The study of quarkonium production in nuclear collisions has a long and rich history, dating back to the original proposal by Matsui and Satz predicting  $J/\psi$  suppression in heavy ion collisions due to Debye screening in the quark–gluon plasma (QGP) [1]. After this proposal, the first  $J/\psi$  measurements in heavy ion collisions were performed in fixed target experiments at the CERN SPS, at a nucleon–nucleon center-of-mass energy of  $\sqrt{s_{NN}} \approx 20 \text{ GeV}$  [2,3]. A similar level of suppression was later observed in gold–gold collisions at the BNL RHIC, at  $\sqrt{s_{NN}} = 200 \text{ GeV}$  [4,5]. At the CERN LHC, the production of charmonium ( $J/\psi$ ,  $\psi(2S)$ ) and bottomonium ( $\Upsilon(1S)$ ,  $\Upsilon(2S)$ ,  $\Upsilon(3S)$ ) states has been studied in lead–lead (PbPb) collisions at  $\sqrt{s_{NN}} = 2.76$  and  $5.02 \text{ TeV}$  [6–12], bringing new elements for the understanding of the medium produced in high-energy heavy ion collisions.

The quarkonium yields can be modified in heavy ion collisions because of several effects [13], including suppression [1] and recombination of charm quark pairs [14] inside the hot matter (QGP), and cold nuclear matter effects. An unambiguous interpretation of the nucleus–nucleus LHC results requires a quantitative understanding of cold nuclear matter effects. The nuclear parton distribution functions (nPDFs) are known to be different from those in a

free proton [15,16]. In addition, gluon radiation induced by multiple parton scattering in the nucleus leads to transverse momentum ( $p_T$ ) broadening and coherent energy loss, resulting in a significant quarkonium suppression in nuclear collisions at all available energies [17,18]. These phenomena are best studied in proton–nucleus collisions, in which hot medium effects, such as those due to the QGP, are likely to be limited.

Many charmonium production measurements have been performed in proton-induced collisions, on several nuclei, at the SPS [19–22], HERA [23], and Tevatron [24]. A global analysis of the fixed-target measurements can be found in Ref. [25]. At RHIC,  $J/\psi$  and  $\psi(2S)$  data in deuteron–gold collisions have been reported by the PHENIX [26] and STAR [27] Collaborations. At the LHC, the cross section of  $J/\psi$  in proton–lead (pPb) collisions at  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$  has been measured by the ALICE [28,29], ATLAS [30], CMS [31], and LHCb [32] Collaborations. A significant suppression of the prompt  $J/\psi$  yield in pPb collisions has been observed at forward rapidity ( $y$ ) and low  $p_T$ , while no strong nuclear effects are reported at backward rapidity, where forward and backward indicate, respectively, the directions of the proton and Pb beams. Measurements of the  $\Upsilon(1S)$  in pPb collisions at  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$  have also been performed by the ALICE [33], ATLAS [34], and LHCb [35] experiments, indicating that the  $\Upsilon(1S)$  state is less suppressed than the  $J/\psi$ .

Additional information can be obtained by studying the behavior of the excited states, which are less tightly bound compared to

<sup>\*</sup> E-mail address: cms-publication-committee-chair@cern.ch.

the ground states and might suffer stronger suppression in heavy ion collisions. At the LHC, the ALICE [36] and CMS [11] Collaborations have reported a stronger suppression of the  $\psi(2S)$  state compared to the  $J/\psi$  in PbPb collisions. In pPb collisions, ALICE [37], ATLAS [34], and LHCb [38] data show that  $\psi(2S)$  suppression, integrated over transverse momentum, is more pronounced than that of the  $J/\psi$ . This observation suggests final-state effects for the excited states, possibly due to inelastic interactions with the medium produced in pPb collisions [39]. In the bottomonium sector, the double yield ratios  $\Upsilon(3S)/\Upsilon(1S)$  and  $\Upsilon(2S)/\Upsilon(1S)$  in pPb relative to pp collisions have been measured by CMS [40] and found to be less than unity, again indicating stronger final-state effects in the production of excited quarkonium states.

This Letter reports measurements of the cross sections for prompt  $\psi(2S)$  production in pp and pPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, with the  $\psi(2S)$  decaying to  $\mu^+\mu^-$ , over the  $p_T$  range 4–30 GeV/c and center-of-mass rapidity range  $-2.4 < y_{CM} < 1.93$ . The data were collected with the CMS detector at the LHC, in 2013 for the pPb sample and in 2015 for the pp sample, corresponding to integrated luminosities of  $34.6 \pm 1.2 \text{ nb}^{-1}$  [41] and  $28.0 \pm 0.6 \text{ pb}^{-1}$  [42], respectively. In addition, the modification of quarkonium production in pPb collisions is quantified by the nuclear modification factor,  $R_{pPb}$ , which is defined as the ratio of the cross sections in pPb and pp collisions divided by the Pb mass number,  $A = 208$ . The  $\psi(2S)$   $R_{pPb}$  is determined as a function of  $y_{CM}$  and  $p_T$ , and is compared to that of the  $J/\psi$  mesons measured at the same center-of-mass energy [31]. This is the first measurement of  $\psi(2S)$   $R_{pPb}$  at  $\sqrt{s_{NN}} = 5.02$  TeV in differential bins of  $p_T$  and  $y_{CM}$  that uses the pp data measured at the same center-of-mass energy.

## 2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume there are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity ( $\eta$ ) coverage provided by the barrel and endcap detectors. The forward hadron (HF) calorimeter uses steel as absorber and quartz fibers as the sensitive material. The two halves of the HF are located at  $\pm 11.2$  m from the nominal interaction point. Together they provide coverage in the range  $3.0 < |\eta| < 5.2$  and also serve as luminosity monitors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid, in the range  $|\eta| < 2.4$ , with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative  $p_T$  resolution for typical muons in this analysis of 1.3–2.0% in the barrel and better than 6% in the endcaps [43]. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [44].

## 3. Event selection

The pPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV correspond to a proton beam energy of 4 TeV and a lead beam energy of 1.58 TeV per nucleon. The proton beam traveled in the  $-\eta$  direction (in the detector coordinate system) in the first part of the run, corresponding to an integrated luminosity  $\mathcal{L}_{int} = 20.7 \text{ nb}^{-1}$ , and in the opposite direction in the second part of the run, corresponding to  $\mathcal{L}_{int} = 13.9 \text{ nb}^{-1}$ . Particles emitted at  $|\eta_{CM}| = 0$  in the nucleon-nucleon center-of-mass frame are detected in the laboratory frame

at  $\eta_{lab} = \pm 0.465$  depending on the proton beam direction. In this paper, data for half of the run were reflected so that positive  $\eta$  always corresponds to the direction of the proton beam. The pp data set, collected at the same collision energy as the pPb sample, corresponds to  $\mathcal{L}_{int} = 28.0 \text{ pb}^{-1}$ . In the pp sample, the dimuons from  $\psi(2S)$  decays are reconstructed within  $|y_{CM}| < 2.4$  and in the same  $p_T$  range as the pPb data,  $4 < p_T < 30 \text{ GeV}/c$ .

Inelastic hadronic collisions are selected by requiring at least one HF tower with more than 3 GeV of total energy in each of the two HF calorimeters. This is not required in pp collisions, which suffer less from photon-induced interactions compared to pPb collisions. The pp and pPb events are further selected to have at least one reconstructed primary vertex composed of two or more associated tracks, excluding the two muons, within 25 cm from the nominal interaction point along the beam axis and within 2 cm in the transverse plane. To reject the beam-gas background events, the fraction of good-quality tracks associated with the primary vertex is required to be larger than 25% when there are more than 10 tracks per event.

The dimuon events are selected by the level-1 trigger, a hardware-based trigger system requiring two muon candidates in the muon detectors with no explicit limitations on their  $p_T$  or  $\eta$ . In the offline analysis, muons are required to be within the following kinematic regions, which ensure single-muon reconstruction efficiencies above 10%:

$$\begin{aligned} p_T^\mu &> 3.3 \text{ GeV}/c && \text{for } |\eta_{lab}^\mu| < 1.2, \\ p_T^\mu &> (4 - [1.1 |\eta_{lab}^\mu|]) \text{ GeV}/c && \text{for } 1.2 < |\eta_{lab}^\mu| < 2.1, \\ p_T^\mu &> 1.3 \text{ GeV}/c && \text{for } 2.1 < |\eta_{lab}^\mu| < 2.4. \end{aligned} \quad (1)$$

The oppositely charged muon pairs are further selected to originate from a common vertex with a  $\chi^2$  probability greater than 1%, and to survive standard identification criteria [43]. In order to remove cosmic-ray muons, the transverse and longitudinal distances of closest approach between the muon trajectory and the reconstructed primary vertex are required to be less than 0.3 cm and 20 cm, respectively. All of these selections are common to both the pp and the pPb data sets.

## 4. Yield extraction

The prompt  $\psi(2S)$  signal extraction procedure is similar to that in previous CMS analyses [8,11], and is the same for the pp and pPb data sets. The dimuon mass distribution is fitted with signal (including both the  $J/\psi$  and  $\psi(2S)$  resonances) and background contributions using an extended unbinned maximum likelihood procedure [45]. While the scope of the present Letter is the measurement of the prompt  $\psi(2S)$  production, the  $J/\psi$  resonance was included in the  $\psi(2S)$  fit to increase the peak fitting stability. It has been checked that the prompt  $J/\psi$  results obtained in this analysis agree with the ones in Ref. [31], which used a different method for separating prompt from nonprompt charmonia. The prompt  $J/\psi$  results of Ref. [31] are the ones used in this Letter for comparison with the new analysis of  $\psi(2S)$  production. Both resonance shapes are modeled by the weighted sum of a Crystal Ball (CB) [46] and a Gaussian function. The CB function,  $g_{CB}(m)$ , combines a Gaussian core and a power law tail with exponent  $n$ , accounting for energy loss due to final-state photon radiation, with a parameter  $\alpha$  defining the transition between the Gaussian and the power law functions:

$$g_{CB}(m) = \begin{cases} \frac{N}{\sqrt{2\pi} \sigma_{CB}} \exp\left(-\frac{(m-m_0)^2}{2\sigma_{CB}^2}\right), & \text{for } \frac{m-m_0}{\sigma_{CB}} > -\alpha; \\ \frac{N}{\sqrt{2\pi} \sigma_{CB}} \left(\frac{n}{|\alpha|}\right)^n \exp\left(-\frac{|\alpha|^2}{2}\right) \\ \times \left(\frac{n}{|\alpha|} - |\alpha| - \frac{m-m_0}{\sigma_{CB}}\right)^{-n}, & \text{for } \frac{m-m_0}{\sigma_{CB}} < -\alpha. \end{cases} \quad (2)$$

The CB and Gaussian functions have independent widths,  $\sigma_{CB}$  and  $\sigma_G$ , to accommodate the dependence of the dimuon invariant mass resolution on the dimuon rapidity and  $p_T$ , but share a common mean  $m_0$  representing the  $J/\psi$  mass. The signal models used for the  $\psi(2S)$  and  $J/\psi$  share the same  $\alpha$  and  $n$  parameters. The mean and the width of the Gaussian model for the  $\psi(2S)$  are obtained from those of the  $J/\psi$ , scaled by their mass ratio ( $m_{\psi(2S)}/m_{J/\psi} = 1.1903$  [47]). The following parameters are left free in the fit:  $m_0$ ,  $\sigma_{CB}$ ,  $\sigma_G$ ,  $N_{J/\psi}$  (the  $J/\psi$  yield),  $N_{\psi(2S)}$  (the  $\psi(2S)$  yield),  $f$  (the relative contribution of the Gaussian and CB functions), and  $\alpha$ . Based on simulation studies, the value of the parameter  $n$  is fixed to 2.1. The parameter  $\alpha$  is left free, covering the variation of signal shapes in each of the  $p_T$  and rapidity bins. The same value for  $f$  is used in the definition of the  $\psi(2S)$  and  $J/\psi$  signal shapes. The underlying background is described by a Chebyshev polynomial of degree  $N$  ( $1 \leq N \leq 3$ ). The degree of the Chebyshev polynomial is obtained in each  $(p_T, y_{CM})$  bin of the analysis using a log-likelihood ratio test. Several alternative fitting procedures have been tested, and the yield variations with respect to the nominal result are included as a systematic uncertainty, as explained in Section 6. The two pPb data sets, corresponding to each proton beam direction, are merged and analyzed together after having verified that the independent results are compatible with each other.

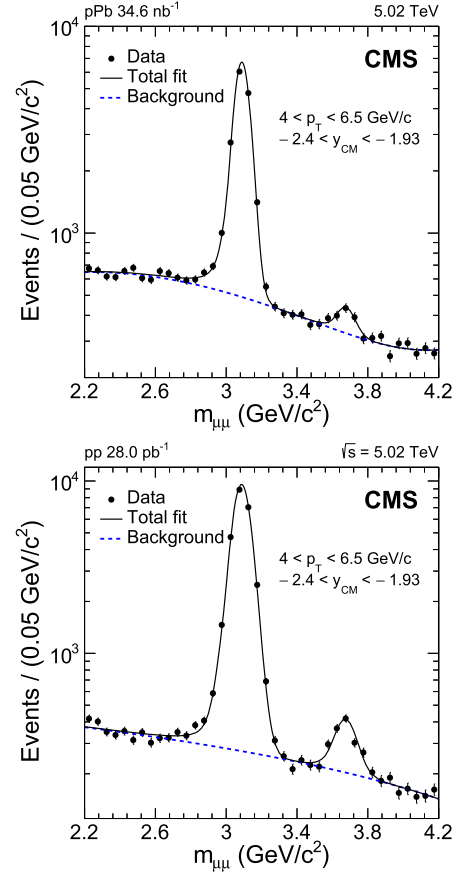
The  $J/\psi$  and  $\psi(2S)$  coming from b hadron decays (nonprompt charmonia) are evaluated using the displacement of the  $\mu^+\mu^-$  vertex from the primary collision vertex. This secondary  $\mu^+\mu^-$  vertex is characterized by the pseudo-proper decay length,

$$\ell_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}, \quad (3)$$

where  $L_{xy}$  is the transverse distance between the primary and dimuon vertices,  $m_{J/\psi}$  is the mass of the  $J/\psi$  [47] (assumed for all muon pairs), and  $p_T$  is the transverse momentum of the dimuon. Prompt charmonia are selected by requiring  $\ell_{J/\psi}$  to be smaller than a threshold value  $l_0$ , which is tuned using simulation separately for the pp and pPb collisions systems, in order to keep 90% of the total prompt charmonia [11]. Since the  $\ell_{J/\psi}$  resolution improves with increasing dimuon  $p_T$ , the  $l_0$  values also depend on  $p_T$ . The  $l_0$  values used remove between 70% and 90% (80% and 90%) of the nonprompt  $\psi(2S)$  in pPb (pp) collisions, from low- to high- $p_T$ .

The yields so obtained have a small nonprompt contamination, which is corrected using the number of simulated events passing and failing the  $\ell_{J/\psi}$  threshold criteria [11]. The full value of this correction is also propagated as a source of systematic uncertainty.

Fig. 1 shows the dimuon invariant mass distributions with the  $J/\psi$  and  $\psi(2S)$  peaks in pPb and pp data, for one of the bins with the smallest signal-to-background ratio (lowest  $p_T$  and most backward  $y$ ), after applying the  $\ell_{J/\psi}$  selection, together with the curves resulting from the fits. The raw prompt  $\psi(2S)$  yield extracted in these bins is  $\sim 300$  for the pPb, and twice as much for the pp samples.



**Fig. 1.** Dimuon invariant mass distribution showing the  $J/\psi$  and  $\psi(2S)$  peaks in pPb (top panel) and pp (bottom panel) data, after applying the  $\ell_{J/\psi}$  selection, for  $-2.4 < y_{CM} < -1.93$  and  $4 < p_T < 6.5 \text{ GeV}/c$ . The fits to the distributions are also shown.

## 5. Acceptance and efficiency corrections

Simulated events are used to obtain the acceptance and efficiency correction factors for the measured  $\psi(2S)$  yields. The events are generated using PYTHIA 6.424 [48] for pPb collisions and PYTHIA 8.209 [49] for pp collisions. The generated particles in the pPb Monte Carlo (MC) are boosted by the  $\beta$  of the center-of-mass system in the laboratory frame, resulting in  $\Delta y = \pm 0.465$ . The prompt  $J/\psi$  and  $\psi(2S)$  are assumed to be produced unpolarized in both pp and pPb collisions, which is supported by measurements in pp collisions at  $\sqrt{s} = 7 \text{ TeV}$  [50,51]. The final-state QED radiation of the decay muons is simulated using PHOTOS 215.5 [52]. Finally, the CMS detector response is simulated using GEANT4 [53].

The acceptance in a given  $(p_T, y_{CM})$  bin is defined as the fraction of generated  $\psi(2S)$  mesons resulting in a detectable muon pair, i.e., passing the single muon selection criteria defined in Eq. (1). The efficiency is given by the fraction of generated and detectable muon pairs that result in a reconstructed muon pair, also passing the trigger and offline selections. The combined  $\psi(2S)$  acceptance and efficiency for pPb (pp) results ranges between 13% (14%) in the lowest  $p_T$  region ( $4.0 < p_T < 6.5 \text{ GeV}/c$ ) and 66% (67%) in the highest  $p_T$  region ( $10.0 < p_T < 30.0 \text{ GeV}/c$ ). It is maximum in the overlap region between barrel and endcap detectors, and decreases to minimum values for  $|y_{CM}| > 2$ .

The individual components of the simulation-based dimuon efficiency (track reconstruction, muon identification and selection, and triggering) are probed using single muons from  $J/\psi$  meson decays in both simulated and collision data, with the *tag-and-probe*

(T&P) method [31,54]. The data-to-simulation ratios of single muon efficiencies obtained from T&P, calculated as a function of muon  $\eta$  and  $p_T$ , are used as weights (*scale factors*) to correct event-by-event the dimuon efficiency. The effect of this correction on the dimuon efficiency is similar for pp and pPb events and ranges from 0.99 to 1.33, with larger corrections at lower  $p_T$  and more forward/backward rapidities.

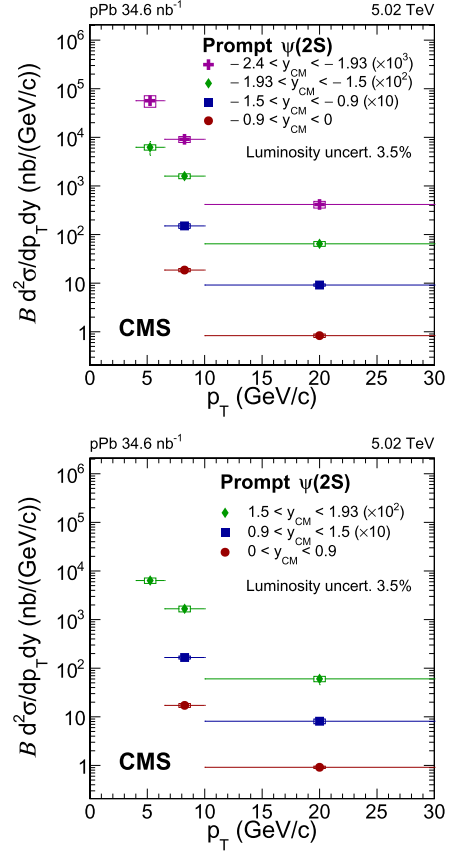
## 6. Systematic uncertainties

The following sources of point-to-point systematic uncertainties are considered for both pp and pPb data: the yield extraction method, given the choice of signal and background models; acceptance and efficiency corrections, including T&P scale factors and the possible difference in the dimuon  $p_T$  spectrum between data and simulation; and the nonprompt charmonia contamination. The evaluation of these systematic uncertainties is described below.

- **Signal shape variation.** This systematic uncertainty is obtained by changing the fitting constraints on the CB shape parameters. In the nominal fits, the CB parameter  $n$  is fixed from simulation,  $n = 2.1$ , and the parameter  $\alpha$  is left free. In a first variation, the parameter  $\alpha$  is fixed to the MC-based value 1.7, and  $n$  is left free. A second variation consists in fixing both parameters to the values extracted from MC,  $n = 2.1$  and  $\alpha = 1.7$ . The maximum difference, in each analysis bin, between the yields extracted with the nominal fit and either of these variations, is taken as a systematic uncertainty.
- **Background shape variation.** The degree  $N$  of the Chebyshev polynomial is changed to  $N + 1$  if  $N < 3$ , and to  $N - 1$  if  $N = 3$ . The systematic uncertainty is estimated as the absolute difference in the yields with respect to the nominal case.
- **Simulated dimuon  $p_T$  spectrum.** The acceptance and efficiency correction factors depend on the shape of the simulated  $\psi(2S)$   $p_T$  distribution; the difference between data and simulation is a source of systematic uncertainty. The ratio of the corrected yields in data and simulation is evaluated as a function of  $p_T$ , for each rapidity bin. Continuous weighting factors are obtained by fitting these data-to-simulation ratios with a linear function in  $p_T$ . The acceptance and efficiency values are evaluated again after weighting the  $p_T$  distribution of the generated  $\psi(2S)$  mesons in the simulation by the function obtained. The difference between the reweighted simulation and the nominal yields is taken as a systematic uncertainty.
- **T&P scale factors.** The statistical uncertainty on the T&P scale factors, as well as systematic uncertainties in their derivation, are accounted for as a systematic uncertainty. These uncertainties are further described in Ref. [31].
- **Nonprompt contamination.** The difference between the prompt meson yields with and without the correction for the residual nonprompt contamination is propagated as a systematic uncertainty.

The systematic uncertainty in the yield extraction, determined by summing the uncertainties from the signal and background shape variations in quadrature, is in the range 1.0–22% and 0.4–6.5% for the pPb and pp results, respectively. This large range is mostly driven by the variation of the signal over background ratio across the analysis bins. The dominant part in this uncertainty is from background modeling, with an average over all the  $p_T$  and  $y_{CM}$  bins of 3.9 (2.4)% and a maximum of 22 (4.9)% for the pPb (pp) results. The average signal modeling contribution is 1.9% and 1.4%, for the pPb and pp results, respectively.

The systematic uncertainty in the acceptance and efficiency correction factors, combining the dimuon  $p_T$  spectrum reweighting



**Fig. 2.** Differential cross section (multiplied by the dimuon branching fraction) of prompt  $\psi(2S)$  production in pPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, as a function of  $p_T$ , in several rapidity bins and separately for backward (top panel) and forward (bottom panel) rapidity regions. Statistical and systematic uncertainties are represented with error bars and boxes, respectively. The fully correlated luminosity uncertainty of 3.5% is not included in the point-by-point uncertainties.

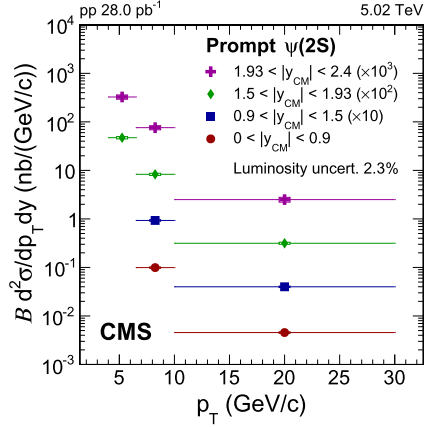
and T&P uncertainties, lies within 2.0–7.4% and 1.9–8.1% for the pPb and pp results, respectively. The prompt selection method induces an uncertainty of 4.5–15% (0.2–8.0%) for the pPb (pp) results, with the maximum value in the lowest  $p_T$  bin in the backward  $y$  region. The total systematic uncertainty, calculated as the sum in quadrature of the individual uncertainties, is in the range 5–26% (4–11%) for the pPb (pp) cross section measurements. In general, the uncertainty is minimum in the highest  $p_T$  bins in the central  $y$  region, and increases when going to lower  $p_T$  and forward/backward  $y$  regions. For the  $R_{pPb}$  measurement, the pp and pPb uncertainties are considered independent and added in quadrature point-by-point. The total systematic uncertainty in this case is in the range 5.0–22.6%.

The global (common to all points) systematic uncertainty due to the uncertainty in the integrated luminosity of the pPb and pp data sets is 3.5% [41] and 2.3% [42], respectively. For the cross section results, this uncertainty is not included to the point-to-point uncertainties, while for the  $R_{pPb}$  results the two numbers are added in quadrature and displayed as a box around  $R_{pPb} = 1$ . The dominant source of uncertainty for the  $R_{pPb}$  measurement is the statistical uncertainty in the pPb data.

## 7. Results

The prompt  $\psi(2S)$  production cross section (multiplied by the  $\psi(2S)$  branching fraction to  $\mu^+\mu^-$ ,  $B(\psi(2S) \rightarrow \mu^+\mu^-)$ ) in the dimuon decay channel is determined as





**Fig. 3.** Differential cross section (multiplied by the dimuon branching fraction) of prompt  $\psi(2S)$  production in pp collisions at  $\sqrt{s} = 5.02$  TeV as a function of  $p_T$ , in four  $y_{CM}$  bins. Statistical and systematic uncertainties are represented with error bars and boxes, respectively. The fully correlated luminosity uncertainty of 2.3% is not included in the point-by-point uncertainties.

$$B(\psi(2S) \rightarrow \mu^+ \mu^-) \frac{d^2\sigma}{dp_T dy_{CM}} = \frac{N_{fit}^{\psi(2S)} / (\text{acc} \varepsilon)}{\mathcal{L}_{int} \Delta p_T \Delta y_{CM}}, \quad (4)$$

where  $N_{fit}^{\psi(2S)}$  is the extracted raw yield of prompt  $\psi(2S)$  mesons in a given  $(p_T, y_{CM})$  bin,  $(\text{acc} \varepsilon)$  is the product of the dimuon acceptance and efficiency described in Section 5, and  $\Delta p_T$  and  $\Delta y_{CM}$  are the widths of the kinematic bin considered.

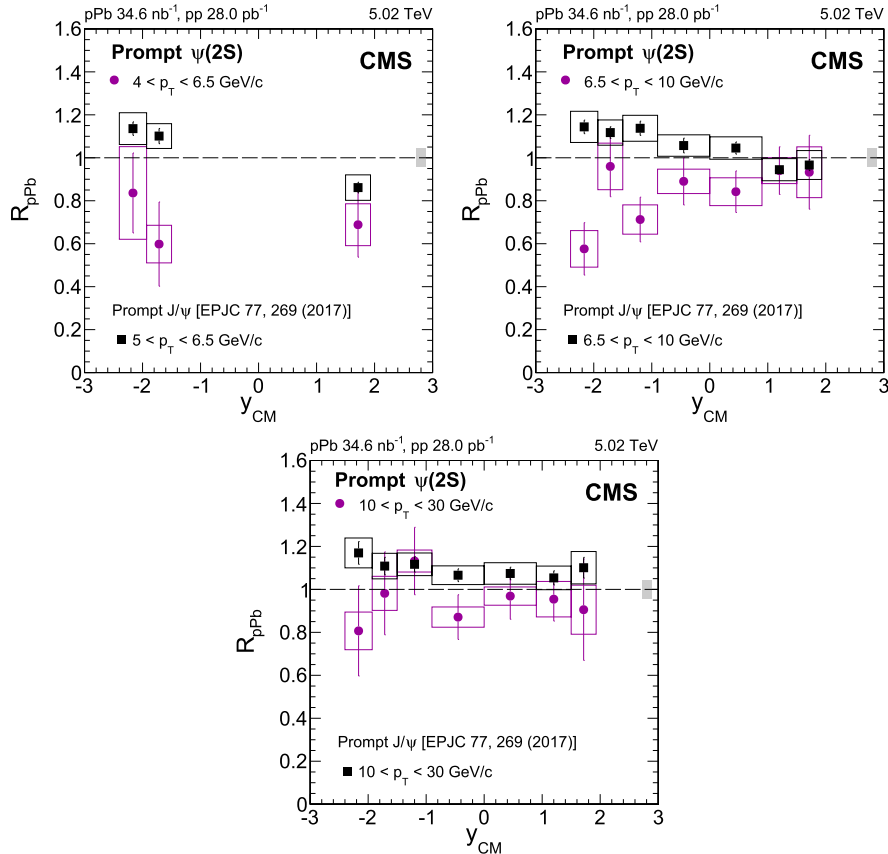
Figs. 2 and 3 show the production cross sections of prompt  $\psi(2S)$  mesons in pPb and pp collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, respectively. The results are given as a function of  $p_T$  and in four rapidity bins, separately for forward (the direction of the proton beam) and backward (the direction of the Pb beam) rapidities in the case of the pPb measurements.

The second observable considered is the nuclear modification factor, defined as

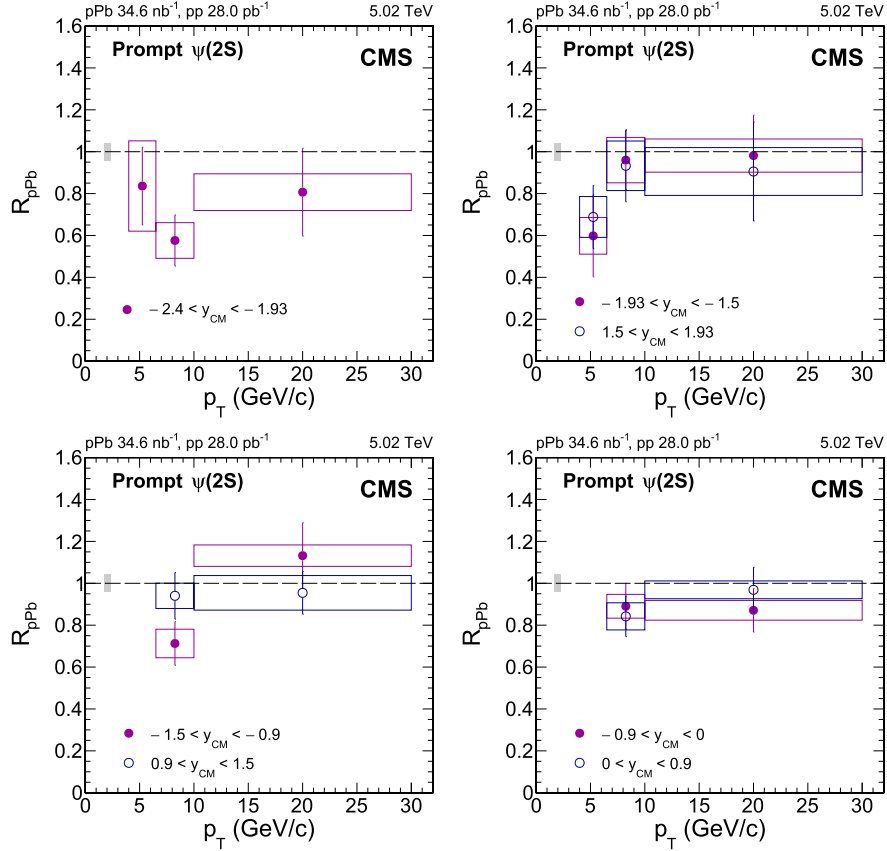
$$R_{pPb}(p_T, y_{CM}) \equiv \frac{(d^2\sigma/dp_T dy_{CM})_{pPb}}{A(d^2\sigma/dp_T dy_{CM})_{pp}}. \quad (5)$$

In the absence of any nuclear effects the measured yield in pPb collisions would be just a superposition of  $A = 208$  (the number of nucleons in the Pb nucleus) pp collisions, and the  $R_{pPb}$  would be one.

Fig. 4 shows the rapidity dependence of the prompt  $\psi(2S)$   $R_{pPb}$  in three  $p_T$  ranges: 4–6.5, 6.5–10, and 10–30 GeV/c. In the backward rapidity region, the prompt  $\psi(2S)$  mesons are suppressed in the intermediate  $p_T$  region, and compatible with unity in the rest. In the forward rapidity region, the  $R_{pPb}$  is consistent with unity for all  $p_T$  bins (although systematically smaller). For comparison, the prompt  $J/\psi$  nuclear modification factor [31] is also shown in Fig. 4. The measured value of  $R_{pPb}$  for prompt  $\psi(2S)$  mesons, when integrated over  $p_T$  and rapidity ( $6.5 < p_T < 30$  GeV/c,  $|y| < 1.6$ ), is  $0.852 \pm 0.037\text{stat} \pm 0.062\text{syst}$ . The prompt  $J/\psi$   $R_{pPb}$  in the same kinematic range is  $1.108 \pm 0.021\text{stat} \pm 0.055\text{syst}$ . The  $R_{pPb}$  for prompt  $J/\psi$  mesons lies systematically above that of the  $\psi(2S)$  state. The difference between the two sets of results was quan-



**Fig. 4.** Rapidity dependence of the prompt  $\psi(2S)$   $R_{pPb}$  in three  $p_T$  ranges. For comparison, the prompt  $J/\psi$  nuclear modification factor [31] is also shown. Statistical and systematic uncertainties are represented with error bars and boxes, respectively. The fully correlated global uncertainty of 4.2% (that affects both charmonia) is displayed as a box around  $R_{pPb} = 1$ .



**Fig. 5.** Transverse momentum dependence of the prompt  $\psi(2S)$   $R_{pPb}$  in four rapidity ranges. Statistical and systematic uncertainties are represented with error bars and boxes, respectively. The fully correlated global uncertainty of 4.2% is displayed as a box around  $R_{pPb} = 1$ .

tified, separately for the backward and forward regions, by comparing the two distributions with a  $\chi^2$ -test, removing the correlated uncertainties from the integrated luminosity. The  $p$ -values are  $< 0.05$  for the lowest two  $p_T$  ranges in the backward rapidity region, and  $> 0.37$  in all the other rapidity and  $p_T$  intervals. This shows that, with a  $p$ -value cutoff of 0.05, the two sets of results are incompatible with each other in the backward rapidity region for  $p_T < 10$  GeV/c, but are compatible in the rest. This suggests the presence of different nuclear effects at play in the production of the excited charmonium state compared to the ground state, in the region of backward rapidity and for  $p_T < 10$  GeV/c.

Fig. 5 shows the  $p_T$  dependence of the prompt  $\psi(2S)$   $R_{pPb}$  in seven rapidity bins, from the most backward  $-2.4 < y_{CM} < -1.93$  to the most forward  $1.5 < y_{CM} < 1.93$  accessible regions. Also in this case, a  $\chi^2$ -test was used to quantify the significance of the difference of the results from unity, in which the fully correlated global uncertainty, displayed as a box around  $R_{pPb} = 1$ , was not included. The  $p$ -values are below 0.05 only in the most backward region. This points to the presence of nuclear effects affecting the  $\psi(2S)$  production in the most backward region that persists at large transverse momentum.

The suppression of prompt  $\psi(2S)$  mesons as compared to prompt  $J/\psi$  mesons, seen in Fig. 4, is compatible with what was measured by the ALICE [37], ATLAS [34], and LHCb [38] Collaborations for  $p_T$  integrated charmonium production in pPb collisions at the same collision energy. While nPDFs [15,16] and coherent energy loss [17,18] are the most discussed effects to explain prompt  $J/\psi$  meson suppression, these two phenomena are expected to affect the  $R_{pPb}$  of prompt  $J/\psi$  and  $\psi(2S)$  mesons by a similar amount. On the contrary, the final-state interaction with

hadrons moving along with the produced charmonium might lead to a stronger suppression of the  $\psi(2S)$  meson, due to its larger size [39,55]. The present measurements, covering wide transverse momentum ( $4 < p_T < 30$  GeV/c) and rapidity ( $-2.4 < y_{CM} < 1.93$ ) ranges, will help understand the origin of the suppression of excited quarkonium states in pPb collisions at the LHC.

## 8. Summary

The data collected by CMS in pp and pPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV are used to investigate prompt  $\psi(2S)$  meson production. The results are based on data samples corresponding to integrated luminosities of  $28.0 \text{ pb}^{-1}$  for pp collisions and  $34.6 \text{ nb}^{-1}$  for pPb collisions. The nuclear modification factor ( $R_{pPb}$ ) of prompt  $\psi(2S)$ , in the kinematic range  $4 < p_T < 30$  GeV/c and  $-2.4 < y_{CM} < 1.93$ , is determined and compared to that of prompt  $J/\psi$  mesons, reported in Ref. [31]. The prompt  $\psi(2S)$  production is suppressed in the intermediate 6.5–10 GeV/c  $p_T$  interval in the region of backward rapidity. The  $R_{pPb}$  is consistent with unity everywhere else (although systematically smaller). The  $R_{pPb}$  values of prompt  $J/\psi$  when compared to those of prompt  $\psi(2S)$  mesons, point to different nuclear effects at play in the production of the excited charmonium state compared to the ground state, in the region of backward rapidity and for  $p_T < 10$  GeV/c. The effects of nuclear parton distribution functions or coherent energy loss are expected to affect the  $R_{pPb}$  of prompt  $J/\psi$  and  $\psi(2S)$  by a similar amount, thus the results hint the presence of final-state interactions with the medium (partonic or hadronic) produced in pPb collisions.

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## The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambroggi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, M. Friedl, V.M. Ghete, J. Hrubec, M. Jeitler<sup>1</sup>, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck<sup>1</sup>, R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz<sup>1</sup>, M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Pieters, M. Van De Klundert, H. Van Haeveermaet, P. Van Mechelen, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium



S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

*Vrije Universiteit Brussel, Brussel, Belgium*

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, E. Starling, C. Vander Velde, P. Vanlaer, D. Vannerom

*Université Libre de Bruxelles, Bruxelles, Belgium*

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov<sup>2</sup>, D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

*Ghent University, Ghent, Belgium*

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*

F.L. Alves, G.A. Alves, L. Brito, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>3</sup>, E. Coelho, E.M. Da Costa, G.G. Da Silveira<sup>4</sup>, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote<sup>3</sup>, F. Torres Da Silva De Araujo, A. Vilela Pereira

*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*

S. Ahuja<sup>a</sup>, C.A. Bernardes<sup>a</sup>, L. Calligaris<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>b</sup>, P.G. Mercadante<sup>b</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>, D. Romero Abad<sup>b</sup>,

<sup>a</sup> Universidade Estadual Paulista, São Paulo, Brazil

<sup>b</sup> Universidade Federal do ABC, São Paulo, Brazil

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

*University of Sofia, Sofia, Bulgaria*

W. Fang<sup>5</sup>, X. Gao<sup>5</sup>, L. Yuan

*Beihang University, Beijing, China*

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

*Institute of High Energy Physics, Beijing, China*

Y. Ban, G. Chen, J. Li, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*

Y. Wang

*Tsinghua University, Beijing, China*

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

*Universidad de Los Andes, Bogota, Colombia*

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*

Z. Antunovic, M. Kovac

*University of Split, Faculty of Science, Split, Croatia*

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov<sup>6</sup>, T. Susa

*Institute Rudjer Boskovic, Zagreb, Croatia*

M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

*University of Cyprus, Nicosia, Cyprus*

M. Finger<sup>7</sup>, M. Finger Jr.<sup>7</sup>

*Charles University, Prague, Czech Republic*

E. Ayala

*Escuela Politecnica Nacional, Quito, Ecuador*

E. Carrera Jarrin

*Universidad San Francisco de Quito, Quito, Ecuador*

Y. Assran<sup>8,9</sup>, M.A. Mahmoud<sup>10,9</sup>, Y. Mohammed<sup>10</sup>

*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, L. Perrini, M. Raidal, C. Veelken

*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

*Department of Physics, University of Helsinki, Helsinki, Finland*

J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

*Helsinki Institute of Physics, Helsinki, Finland*

T. Tuuva

*Lappeenranta University of Technology, Lappeenranta, Finland*

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, M. Machet, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*

A. Abdulsalam<sup>11</sup>, C. Amendola, I. Antropov, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, I. Kucher, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, Y. Yilmaz, A. Zabi, A. Zghiche

*Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France*

J.-L. Agram<sup>12</sup>, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte<sup>12</sup>, F. Drouhin<sup>12</sup>, J.-C. Fontaine<sup>12</sup>, D. Gelé, U. Goerlach, M. Jansová, P. Juillot, A.-C. Le Bihan, N. Tonon, P. Van Hove

*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*

S. Gadrat

*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*

S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov<sup>13</sup>, V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*

T. Toriashvili<sup>14</sup>

*Georgian Technical University, Tbilisi, Georgia*

Z. Tsamalaidze<sup>7</sup>

*Tbilisi State University, Tbilisi, Georgia*

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov<sup>13</sup>

*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*

A. Albert, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, A. Schmidt, D. Teyssier, S. Thüer

*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*

G. Flügge, O. Hlushchenko, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, H. Sert, A. Stahl<sup>15</sup>

*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras<sup>16</sup>, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pados, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo<sup>17</sup>, A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, A. Lelek, T. Lenz, K. Lipka, W. Lohmann<sup>18</sup>, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, S.K. Pflitsch, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, N. Stefaniuk, H. Tholen, A. Vagnerini, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

R. Aggleton, S. Bein, A. Benecke, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaupt, M. Niedziela, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, D. Troendle, E. Usai, A. Vanhoefer, B. Vormwald

*University of Hamburg, Hamburg, Germany*

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann<sup>15</sup>, S.M. Heindl, U. Husemann, F. Kassel<sup>15</sup>, I. Katkov<sup>13</sup>, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

*Institut für Experimentelle Teilchenphysik, Karlsruhe, Germany*

G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, I. Topsis-Giotis

*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*

G. Karathanasis, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi, K. Vellidis

*National and Kapodistrian University of Athens, Athens, Greece*

K. Kousouris, I. Papakrivopoulos, Y. Tsiopolitis

*National Technical University of Athens, Athens, Greece*

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

*University of Ioánnina, Ioánnina, Greece*

M. Csanad, N. Filipovic, G. Pasztor, O. Surányi, G.I. Veres

*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*

G. Bencze, C. Hajdu, D. Horvath<sup>19</sup>, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi<sup>†</sup>

*Wigner Research Centre for Physics, Budapest, Hungary*

N. Beni, S. Czellar, J. Karancsi<sup>21</sup>, A. Makovec, J. Molnar, Z. Szillasi

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

M. Bartók<sup>20</sup>, P. Raics, Z.L. Trocsanyi, B. Ujvari

*Institute of Physics, University of Debrecen, Debrecen, Hungary*

S. Choudhury, J.R. Komaragiri

*Indian Institute of Science (IISc), Bangalore, India*

S. Bahinipati<sup>22</sup>, P. Mal, K. Mandal, A. Nayak<sup>23</sup>, D.K. Sahoo<sup>22</sup>, S.K. Swain

*National Institute of Science Education and Research, HBNI, Bhubaneswar, India*

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, S. Sharma, J.B. Singh, G. Walia

*Panjab University, Chandigarh, India*

A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

*University of Delhi, Delhi, India*

R. Bhardwaj<sup>24</sup>, M. Bharti, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep<sup>24</sup>, D. Bhowmik, S. Dey, S. Dutt<sup>24</sup>, S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, B. Singh, S. Thakur<sup>24</sup>

*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*



P.K. Behera

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, R. Ravindra Kumar Verma, N. Sur, B. Sutar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity<sup>25</sup>, G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar<sup>25</sup>

Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kotheekar, S. Pandey, A. Rane, S. Sharma

Indian Institute of Science Education and Research (IISER), Pune, India

S. Chenarani<sup>26</sup>, E. Eskandari Tadavani, S.M. Etesami<sup>26</sup>, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>27</sup>, M. Zeinali

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, A. Di Florio<sup>a,b</sup>, F. Errico<sup>a,b</sup>, L. Fiore<sup>a</sup>, A. Gelmi<sup>a,b</sup>, G. Iaselli<sup>a,c</sup>, S. Lezki<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, A. Sharma<sup>a</sup>, L. Silvestris<sup>a,15</sup>, R. Venditti<sup>a</sup>, P. Verwilligen<sup>a</sup>, G. Zito<sup>a</sup>

<sup>a</sup> INFN Sezione di Bari, Bari, Italy

<sup>b</sup> Università di Bari, Bari, Italy

<sup>c</sup> Politecnico di Bari, Bari, Italy

G. Abbiendi<sup>a</sup>, C. Battilana<sup>a,b</sup>, D. Bonacorsi<sup>a,b</sup>, L. Borghonovi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, S.S. Chhibra<sup>a,b</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a</sup>

<sup>a</sup> INFN Sezione di Bologna, Bologna, Italy

<sup>b</sup> Università di Bologna, Bologna, Italy

S. Albergo<sup>a,b</sup>, A. Di Mattia<sup>a</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Catania, Catania, Italy

<sup>b</sup> Università di Catania, Catania, Italy

G. Barbagli<sup>a</sup>, K. Chatterjee<sup>a,b</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, G. Latino, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, L. Russo<sup>a,28</sup>, G. Sguazzoni<sup>a</sup>, D. Strom<sup>a</sup>, L. Viliani<sup>a</sup>

<sup>a</sup> INFN Sezione di Firenze, Firenze, Italy

<sup>b</sup> Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera<sup>15</sup>

INFN Laboratori Nazionali di Frascati, Frascati, Italy

F. Ferro<sup>a</sup>, F. Ravera<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Genova, Genova, Italy

<sup>b</sup> Università di Genova, Genova, Italy

A. Benaglia<sup>a</sup>, A. Beschi<sup>b</sup>, L. Brianza<sup>a,b</sup>, F. Brivio<sup>a,b</sup>, V. Ciriolo<sup>a,b,15</sup>, M.E. Dinardo<sup>a,b</sup>, S. Fiorendi<sup>a,b</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, M. Malberti<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, R.A. Manzoni<sup>a,b</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Pigazzini<sup>a,b,29</sup>, S. Ragazzi<sup>a,b</sup>, T. Tabarelli de Fatis<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Milano-Bicocca, Milano, Italy

<sup>b</sup> Università di Milano-Bicocca, Milano, Italy

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, A. Di Crescenzo<sup>a,b</sup>, S. Di Guida<sup>a,d,15</sup>, F. Fabozzi<sup>a,c</sup>, F. Fienga<sup>a,b</sup>, G. Galati<sup>a,b</sup>, A.O.M. Iorio<sup>a,b</sup>, W.A. Khan<sup>a</sup>, L. Lista<sup>a</sup>, S. Meola<sup>a,d,15</sup>, P. Paolucci<sup>a,15</sup>, C. Sciacca<sup>a,b</sup>, E. Voevodina<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Napoli, Napoli, Italy

<sup>b</sup> Università di Napoli 'Federico II', Napoli, Italy

<sup>c</sup> Università della Basilicata, Potenza, Italy

<sup>d</sup> Università G. Marconi, Roma, Italy

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a</sup>, L. Benato<sup>a,b</sup>, D. Bisello<sup>a,b</sup>, A. Boletti<sup>a,b</sup>, A. Bragagnolo, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, M. Dall'Osso<sup>a,b</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, U. Dosselli<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino<sup>a</sup>, S. Lacaprara<sup>a</sup>, P. Lujan, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, R. Rossin<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, A. Tiko, E. Torassa<sup>a</sup>, M. Zanetti<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Padova, Padova, Italy

<sup>b</sup> Università di Padova, Padova, Italy

<sup>c</sup> Università di Trento, Trento, Italy

A. Braghieri<sup>a</sup>, A. Magnani<sup>a</sup>, P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, M. Ressegotti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a,b</sup>, P. Vitulo<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Pavia, Pavia, Italy

<sup>b</sup> Università di Pavia, Pavia, Italy

L. Alunni Solestizi<sup>a,b</sup>, M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, C. Cecchi<sup>a,b</sup>, D. Ciangottini<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, E. Manoni<sup>a</sup>, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Rossi<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, D. Spiga<sup>a</sup>

<sup>a</sup> INFN Sezione di Perugia, Perugia, Italy

<sup>b</sup> Università di Perugia, Perugia, Italy

K. Androssov<sup>a</sup>, P. Azzurri<sup>a</sup>, G. Bagliesi<sup>a</sup>, L. Bianchini<sup>a</sup>, T. Boccali<sup>a</sup>, L. Borrello, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,b</sup>, R. Dell'Orso<sup>a</sup>, G. Fedi<sup>a</sup>, L. Giannini<sup>a,c</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a</sup>, F. Ligabue<sup>a,c</sup>, T. Lomtadze<sup>a</sup>, E. Manca<sup>a,c</sup>, G. Mandorli<sup>a,c</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, A. Rizzi<sup>a,b</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

<sup>a</sup> INFN Sezione di Pisa, Pisa, Italy

<sup>b</sup> Università di Pisa, Pisa, Italy

<sup>c</sup> Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, M. Cipriani<sup>a,b</sup>, N. Daci<sup>a</sup>, D. Del Re<sup>a,b</sup>, E. Di Marco<sup>a,b</sup>, M. Diemoz<sup>a</sup>, S. Gelli<sup>a,b</sup>, E. Longo<sup>a,b</sup>, B. Marzocchi<sup>a,b</sup>, P. Meridiani<sup>a</sup>, G. Organtini<sup>a,b</sup>, F. Pandolfi<sup>a</sup>, R. Paramatti<sup>a,b</sup>, F. Preiato<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Roma, Rome, Italy

<sup>b</sup> Sapienza Università di Roma, Rome, Italy

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, N. Bartosik<sup>a</sup>, R. Bellan<sup>a,b</sup>, C. Biino<sup>a</sup>, N. Cartiglia<sup>a</sup>, F. Cenna<sup>a,b</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, A. Degano<sup>a,b</sup>, N. Demaria<sup>a</sup>, B. Kiani<sup>a,b</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, E. Monteil<sup>a,b</sup>, M. Monteno<sup>a</sup>, M.M. Obertino<sup>a,b</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G.L. Pinna Angioni<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, K. Shchelina<sup>a,b</sup>, V. Sola<sup>a</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>

<sup>a</sup> INFN Sezione di Torino, Torino, Italy<sup>b</sup> Università di Torino, Torino, Italy<sup>c</sup> Università del Piemonte Orientale, Novara, ItalyS. Belforte <sup>a</sup>, V. Candelise <sup>a,b</sup>, M. Casarsa <sup>a</sup>, F. Cossutti <sup>a</sup>, G. Della Ricca <sup>a,b</sup>, F. Vazzoler <sup>a,b</sup>, A. Zanetti <sup>a</sup><sup>a</sup> INFN Sezione di Trieste, Trieste, Italy<sup>b</sup> Università di Trieste, Trieste, Italy

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, Y.C. Yang

Kyungpook National University, Republic of Korea

H. Kim, D.H. Moon, G. Oh

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

J. Goh, T.J. Kim

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

H. Kim

Sejong University, Seoul, Republic of Korea

J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

Seoul National University, Seoul, Republic of Korea

H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

University of Seoul, Seoul, Republic of Korea

Y. Choi, C. Hwang, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenias, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali <sup>30</sup>, F. Mohamad Idris <sup>31</sup>, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

M.C. Duran-Osuna, H. Castilla-Valdez, E. De La Cruz-Burelo, G. Ramirez-Sanchez, I. Heredia-De La Cruz <sup>32</sup>, R.I. Rabadan-Trejo, R. Lopez-Fernandez, J. Mejia Guisao, R. Reyes-Almanza, A. Sanchez-Hernandez

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

**D. Krofcheck***University of Auckland, Auckland, New Zealand***S. Bheesette, P.H. Butler***University of Canterbury, Christchurch, New Zealand***A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas***National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan***H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, P. Traczyk, P. Zalewski***National Centre for Nuclear Research, Swierk, Poland***K. Bunkowski, A. Byszuk<sup>33</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak***Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland***P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadrucchio, J. Varela***Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal***A. Baginyan, P. Bunin, I. Golutvin, V. Karjavin, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev<sup>34,35</sup>, V.V. Mitsyn, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, V. Trofimov, B.S. Yuldashev<sup>36</sup>, A. Zarubin, V. Zhiltsov***Joint Institute for Nuclear Research, Dubna, Russia***V. Golovtsov, Y. Ivanov, V. Kim<sup>37</sup>, E. Kuznetsova<sup>38</sup>, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vasilov, A. Vorobyev***Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia***Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tisov, A. Toropin***Institute for Nuclear Research, Moscow, Russia***V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin***Institute for Theoretical and Experimental Physics, Moscow, Russia***T. Aushev, A. Bylinkin<sup>35</sup>***Moscow Institute of Physics and Technology, Moscow, Russia***R. Chistov<sup>39</sup>, M. Danilov<sup>39</sup>, P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii***National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia***V. Andreev, M. Azarkin<sup>35</sup>, I. Dremin<sup>35</sup>, M. Kirakosyan<sup>35</sup>, S.V. Rusakov, A. Terkulov***P.N. Lebedev Physical Institute, Moscow, Russia***A. Baskakov, A. Belyaev, E. Boos, A. Demiyanov, A. Ershov, A. Gribushin, O. Kodolova, V. Korotkikh, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan***Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*



V. Blinov<sup>40</sup>, T. Dimova<sup>40</sup>, L. Kardapoltsev<sup>40</sup>, D. Shtol<sup>40</sup>, Y. Skovpen<sup>40</sup>

*Novosibirsk State University (NSU), Novosibirsk, Russia*

I. Azhgirey, I. Bayshev, S. Bitiukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

*State Research Center of Russian Federation, Institute for High Energy Physics of NRC 'Kurchatov Institute', Protvino, Russia*

A. Babaev

*National Research Tomsk Polytechnic University, Tomsk, Russia*

P. Adzic<sup>41</sup>, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*

J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi

*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*

C. Albajar, J.F. de Trocóniz

*Universidad Autónoma de Madrid, Madrid, Spain*

J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, P. Vischia, J.M. Vizan Garcia

*Universidad de Oviedo, Oviedo, Spain*

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita<sup>42</sup>, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, D. Gulhan, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban<sup>18</sup>, J. Kieseler, V. Knünz, A. Kornmayer, M. Krammer<sup>1</sup>, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic<sup>43</sup>, F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, F. Pantaleo<sup>15</sup>, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabadý, A. Racz, T. Reis, G. Rolandi<sup>44</sup>, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas<sup>45</sup>, A. Stakia, J. Steggemann, M. Tosi, D. Treille, A. Tsiros, V. Veckalns<sup>46</sup>, M. Verweij, W.D. Zeuner

*CERN, European Organization for Nuclear Research, Geneva, Switzerland*

W. Bertl<sup>†</sup>, L. Caminada<sup>47</sup>, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

*Paul Scherrer Institut, Villigen, Switzerland*

M. Backhaus, L. Bäni, P. Berger, B. Casal, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, T. Klijnsma, W. Lustermann, M. Marionneau,

M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Reichmann, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

*ETH Zurich – Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*

T.K. Aarrestad, C. AMSler<sup>48</sup>, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, I. Neutelings, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

*Universität Zürich, Zurich, Switzerland*

Y.H. Chang, K.y. Cheng, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

*National Central University, Chung-Li, Taiwan*

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Arun Kumar, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J.f. Tsai

*National Taiwan University (NTU), Taipei, Taiwan*

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*

A. Bat, F. Boran, S. Cerci<sup>49</sup>, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos<sup>50</sup>, E.E. Kangal<sup>51</sup>, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir<sup>52</sup>, S. Ozturk<sup>53</sup>, D. Sunar Cerci<sup>49</sup>, B. Tali<sup>49</sup>, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*

B. Isildak<sup>54</sup>, G. Karapinar<sup>55</sup>, M. Yalvac, M. Zeyrek

*Middle East Technical University, Physics Department, Ankara, Turkey*

I.O. Atakisi, E. Gülmez, M. Kaya<sup>56</sup>, O. Kaya<sup>57</sup>, S. Tekten, E.A. Yetkin<sup>58</sup>

*Bogazici University, Istanbul, Turkey*

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen<sup>59</sup>

*Istanbul Technical University, Istanbul, Turkey*

B. Grynyov

*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*

L. Levchuk

*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*

T. Alexander, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold<sup>60</sup>, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor

*University of Bristol, Bristol, United Kingdom*

A. Belyaev<sup>61</sup>, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

*Rutherford Appleton Laboratory, Didcot, United Kingdom*

G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash<sup>62</sup>, A. Nikitenko<sup>6</sup>, V. Palladino, M. Pesaresi, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, T. Strebler, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta<sup>63</sup>, T. Virdee<sup>15</sup>, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

*Imperial College, London, United Kingdom*

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

*Brunel University, Uxbridge, United Kingdom*

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

*Baylor University, Waco, USA*

R. Bartek, A. Dominguez

*Catholic University of America, Washington DC, USA*

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

*The University of Alabama, Tuscaloosa, USA*

D. Arcaro, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

*Boston University, Boston, USA*

G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan<sup>64</sup>, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

*Brown University, Providence, USA*

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

*University of California, Davis, Davis, USA*

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

*University of California, Los Angeles, USA*

E. Bouvier, K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

*University of California, Riverside, Riverside, USA*

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech<sup>65</sup>, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

*University of California, San Diego, La Jolla, USA*

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, M. Citron, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, S. Wang, J. Yoo

*University of California, Santa Barbara – Department of Physics, Santa Barbara, USA*

D. Anderson, A. Bornheim, J. Bunn, J.M. Lawhorn, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

*California Institute of Technology, Pasadena, USA*

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

*Carnegie Mellon University, Pittsburgh, USA*

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, E. MacDonald, T. Mulholland, K. Stenson, K.A. Ulmer, S.R. Wagner

*University of Colorado Boulder, Boulder, USA*

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. McDermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

*Cornell University, Ithaca, USA*

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla<sup>†</sup>, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro<sup>66</sup>, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck, W. Wu

*Fermi National Accelerator Laboratory, Batavia, USA*

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, L. Thomas, J. Wang, S. Wang

*University of Florida, Gainesville, USA*

Y.R. Joshi, S. Linn

*Florida International University, Miami, USA*

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay

*Florida State University, Tallahassee, USA*

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

*Florida Institute of Technology, Melbourne, USA*

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, C. Mills, I.D. Sandoval Gonzalez, M.B. Tonjes, N. Varelas, H. Wang, Z. Wu, J. Zhang

*University of Illinois at Chicago (UIC), Chicago, USA*

B. Bilki<sup>67</sup>, W. Clarida, K. Dilsiz<sup>68</sup>, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>69</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul<sup>70</sup>, Y. Onel, F. Ozok<sup>71</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

*The University of Iowa, Iowa City, USA*

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

*Johns Hopkins University, Baltimore, USA*



A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

*The University of Kansas, Lawrence, USA*

A. Ivanov, K. Kaadze, Y. Maravin, A. Modak, A. Mohammadi, L.K. Saini, N. Skhirtladze

*Kansas State University, Manhattan, USA*

F. Rebassoo, D. Wright

*Lawrence Livermore National Laboratory, Livermore, USA*

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

*University of Maryland, College Park, USA*

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch, S. Zhaozhong

*Massachusetts Institute of Technology, Cambridge, USA*

A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

*University of Minnesota, Minneapolis, USA*

J.G. Acosta, S. Oliveros

*University of Mississippi, Oxford, USA*

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

*University of Nebraska-Lincoln, Lincoln, USA*

A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

*State University of New York at Buffalo, Buffalo, USA*

E. Barberis, C. Freer, A. Hortiangtham, A. Massironi, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

*Northeastern University, Boston, USA*

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

*Northwestern University, Evanston, USA*

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>34</sup>, M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

*University of Notre Dame, Notre Dame, USA*

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer, H.W. Wulsin

*The Ohio State University, Columbus, USA*

S. Cooperstein, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, A. Kalogeropoulos, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

*Princeton University, Princeton, USA*

S. Malik, S. Norberg

*University of Puerto Rico, Mayaguez, USA*

A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

*Purdue University, West Lafayette, USA*

T. Cheng, J. Dolen, N. Parashar

*Purdue University Northwest, Hammond, USA*

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Guilbaud, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

*Rice University, Houston, USA*

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, R. Taus, M. Verzetti

*University of Rochester, Rochester, USA*

A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

*Rutgers, The State University of New Jersey, Piscataway, USA*

A.G. Delannoy, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

*University of Tennessee, Knoxville, USA*

O. Bouhali<sup>72</sup>, A. Castaneda Hernandez<sup>72</sup>, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>73</sup>, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov

*Texas A&M University, College Station, USA*

N. Akchurin, J. Damgov, F. De Guio, P.R. Duderø, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

*Texas Tech University, Lubbock, USA*

S. Greene, A. Gurrola, R. Janjam, W. Johns, A. Melo, H. Ni, K. Padeken, J.D. Ruiz Alvarez, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

*Vanderbilt University, Nashville, USA*

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

*University of Virginia, Charlottesville, USA*

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

*Wayne State University, Detroit, USA*

M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbbers, A. Lanaro, A. Levine, K. Long, R. Loveless, T. Ruggles, A. Savin, N. Smith, W.H. Smith, N. Woods

University of Wisconsin – Madison, Madison, WI, USA

<sup>†</sup> Deceased.

<sup>1</sup> Also at Vienna University of Technology, Vienna, Austria.

<sup>2</sup> Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

<sup>3</sup> Also at Universidade Estadual de Campinas, Campinas, Brazil.

<sup>4</sup> Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

<sup>5</sup> Also at Université Libre de Bruxelles, Bruxelles, Belgium.

<sup>6</sup> Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

<sup>7</sup> Also at Joint Institute for Nuclear Research, Dubna, Russia.

<sup>8</sup> Also at Suez University, Suez, Egypt.

<sup>9</sup> Now at British University in Egypt, Cairo, Egypt.

<sup>10</sup> Also at Fayoum University, El-Fayoum, Egypt.

<sup>11</sup> Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia.

<sup>12</sup> Also at Université de Haute Alsace, Mulhouse, France.

<sup>13</sup> Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

<sup>14</sup> Also at Tbilisi State University, Tbilisi, Georgia.

<sup>15</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

<sup>16</sup> Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

<sup>17</sup> Also at University of Hamburg, Hamburg, Germany.

<sup>18</sup> Also at Brandenburg University of Technology, Cottbus, Germany.

<sup>19</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

<sup>20</sup> Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

<sup>21</sup> Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

<sup>22</sup> Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.

<sup>23</sup> Also at Institute of Physics, Bhubaneswar, India.

<sup>24</sup> Also at Shoolini University, Solan, India.

<sup>25</sup> Also at University of Visva-Bharati, Santiniketan, India.

<sup>26</sup> Also at Isfahan University of Technology, Isfahan, Iran.

<sup>27</sup> Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

<sup>28</sup> Also at Università degli Studi di Siena, Siena, Italy.

<sup>29</sup> Also at INFN Sezione di Milano-Bicocca <sup>a</sup>, Università di Milano-Bicocca <sup>b</sup>, Milano, Italy.

<sup>30</sup> Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.

<sup>31</sup> Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.

<sup>32</sup> Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.

<sup>33</sup> Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

<sup>34</sup> Also at Institute for Nuclear Research, Moscow, Russia.

<sup>35</sup> Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.

<sup>36</sup> Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.

<sup>37</sup> Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

<sup>38</sup> Also at University of Florida, Gainesville, USA.

<sup>39</sup> Also at P.N. Lebedev Physical Institute, Moscow, Russia.

<sup>40</sup> Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.

<sup>41</sup> Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.

<sup>42</sup> Also at INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy.

<sup>43</sup> Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

<sup>44</sup> Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.

<sup>45</sup> Also at National and Kapodistrian University of Athens, Athens, Greece.

<sup>46</sup> Also at Riga Technical University, Riga, Latvia.

<sup>47</sup> Also at Universität Zürich, Zurich, Switzerland.

<sup>48</sup> Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.

<sup>49</sup> Also at Adiyaman University, Adiyaman, Turkey.

<sup>50</sup> Also at Istanbul Aydin University, Istanbul, Turkey.

<sup>51</sup> Also at Mersin University, Mersin, Turkey.

<sup>52</sup> Also at Piri Reis University, Istanbul, Turkey.

<sup>53</sup> Also at Gaziosmanpasa University, Tokat, Turkey.

<sup>54</sup> Also at Ozyegin University, Istanbul, Turkey.

<sup>55</sup> Also at Izmir Institute of Technology, Izmir, Turkey.

<sup>56</sup> Also at Marmara University, Istanbul, Turkey.

<sup>57</sup> Also at Kafkas University, Kars, Turkey.

<sup>58</sup> Also at Istanbul Bilgi University, Istanbul, Turkey.

<sup>59</sup> Also at Hacettepe University, Ankara, Turkey.

<sup>60</sup> Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

<sup>61</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

- <sup>62</sup> Also at Monash University, Faculty of Science, Clayton, Australia.
- <sup>63</sup> Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- <sup>64</sup> Also at Bethel University, St. Paul, USA.
- <sup>65</sup> Also at Utah Valley University, Orem, USA.
- <sup>66</sup> Also at Purdue University, West Lafayette, USA.
- <sup>67</sup> Also at Beykent University, Istanbul, Turkey.
- <sup>68</sup> Also at Bingöl University, Bingöl, Turkey.
- <sup>69</sup> Also at Erzincan University, Erzincan, Turkey.
- <sup>70</sup> Also at Sinop University, Sinop, Turkey.
- <sup>71</sup> Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- <sup>72</sup> Also at Texas A&M University at Qatar, Doha, Qatar.
- <sup>73</sup> Also at Kyungpook National University, Daegu, Republic of Korea.